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DYNAMIC FRACTURE BEHAVIOR OF STRUCTURAL MATERIALS(U)  
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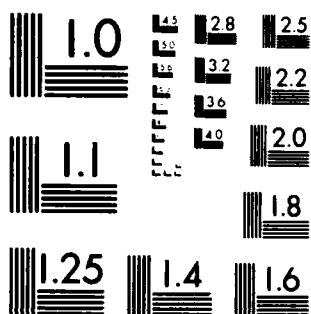
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March 1983

SRI International  
Second Annual Report

DYNAMIC FRACTURE BEHAVIOR OF STRUCTURAL MATERIALS

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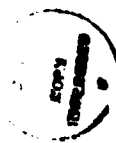
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dynamic propagation toughness,  $K_{ID}$ , by measuring the temperature histories in material near the tip of a fast running crack.

During the second research year, the suitability of the impacted unsupported edge-cracked bend specimen for  $K_{ID}$  measurements has been demonstrated. An experimental parametric study of the specimen dimensions has been performed to optimize the stress intensity amplitude achievable with the bend configuration and to obtain the desired duration of loading. The study has shown that proper choice of the specimen dimensions eliminates undesirable higher order vibrations of the specimen. The experimental investigation has been backed by a simple analysis that should allow the prediction of the stress intensity history from the knowledge of the specimen dimensions, maximum impact load, and the impact velocity.

Dynamic crack propagation experiments were also performed. The crack velocity and the stress intensity at the running crack tip,  $K_I^{dyn}$ , were measured by means of resistance strain gages. The propagation toughness  $K_{ID}$  was deduced from temperature measurements with thermocouples and thermistors. The tests yielded  $K_{ID}$  values that were consistently lower than the measured  $K_I^{dyn}$  by 20% to 40%. These large discrepancies were traced back to the thermoelastic cooling of the specimen in the loading phase of the experiment and immediately after crack arrest. Based on the experience gained in these experiments, the test procedure will be modified to guarantee reliable temperature measurements in future crack propagation experiments.

The research efforts on dynamic crack initiation and crack propagation will continue in the next two years and several structural alloys will be investigated.



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## I SUMMARY

The goals of this project are to first develop and apply procedures for obtaining more accurate measures of dynamic fracture initiation and propagation toughnesses and then to establish the relationship between them. We obtain the dynamic initiation toughness,  $K_{ID}$ , by impacting unsupported edge-cracked bend specimens and using minimum-time crack-instability criteria, and we obtain the dynamic propagation toughness,  $K_{ID}$ , by measuring the temperature histories in material near the tip of a fast running crack.

During the second research year, the suitability of the impacted unsupported edge-cracked bend specimen for  $K_{ID}$  measurements has been demonstrated. An experimental parametric study of the specimen dimensions has been performed to optimize the stress intensity amplitude achievable with the bend configuration and to obtain the desired duration of loading. The study has shown that proper choice of the specimen dimensions eliminates undesirable higher order vibrations of the specimen. The experimental investigation has been backed by a simple analysis that should allow the prediction of the stress intensity history from the knowledge of the specimen dimensions, maximum impact load, and the impact velocity.

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MATTHEW J. KLEPPER

1 Chief, Technical Information Division

## II INTRODUCTION

Structures used by the U.S. Air Force must be designed to resist catastrophic fracture when subjected to dynamic loads. For example, aircraft components may experience short stress pulses from airborne debris, military projectiles, or intense bursts of laser or x-ray radiation. Landing gear and aircraft retaining cables on carrier ships experience dynamic loads at the end of each flight.

A related dynamic fracture problem concerns rapidly running cracks. For example, it is often desirable to know whether a crack, once initiated, will arrest before it reaches a component boundary and thereby preserve the integrity of the structure. Thus, to ensure safe design of Air Force structures, a knowledge of the dynamic fracture behavior of the component materials is necessary. The research being conducted in this program is aimed at improving our understanding of dynamic fracture. Emphasis is put on the accurate characterization of material resistance to crack initiation under dynamic loading ( $K_{Id}$  measurements) and to rapid crack propagation ( $K_{ID}$  measurements). This annual report reviews the specific program objectives and summarizes the progress during the second research year.

### III OBJECTIVES

To obtain more accurate measures of dynamic fracture initiation and propagation toughnesses and to establish the relationship between them, we proposed to accomplish the following research tasks in a five-year program:

- Task 1 - Based on the new understanding of the role of load duration in crack instability behavior, develop a simple test procedure to obtain reliable fracture toughness values at strain rates representative of impact loading.
- Task 2 - Generate the necessary data to develop a reliable theory for dynamic crack instability. In particular, measure the minimum time for instability for different K-histories.
- Task 3 - Obtain values of the propagation toughness  $K_{ID}$  by means of heat of fracture measurements and establish the relationship between  $K_{ID}$  and the dynamic fracture toughness associated with high loading rate initiation,  $K_{IQ}$ .
- Task 4 - Measure critical conditions and establish criteria for crack instability under mixed-mode, short-pulse loads.

This year we focused on Tasks 1, 2, and 3, and the progress to date is described in the next section.



#### IV PROGRESS

##### Toughness and Minimum Time to Fracture Measurements for Impact-Loaded Cracks

The results of a previous AFOSR-sponsored research program defined the conditions of pulse duration and crack length for valid dynamic fracture toughness measurements.<sup>1</sup> It was shown that well-established static stress intensity expressions apply to dynamic loading situations when the crack length  $a_0$  and pulse duration  $T_0$  are such that  $c_1 T_0 / a_0 > 40$ , where  $c_1$  is the longitudinal wave velocity in the specimen. These results provide the criteria necessary to design a specimen and impact device for unambiguous  $K_{Id}$  determinations.

The previous work showed further that for combinations of crack length and pulse duration satisfying the inequality  $c_1 T_0 / a_0 < 3$ , the crack tip stress intensity history had a constant shape, dependent only on stress pulse amplitude and independent of crack length. Crack instability was postulated to occur only if the stress intensity exceeds the dynamic fracture toughness for an (as yet poorly defined) minimum time.

During this program, we plan to use the new insights we gained into the dynamic crack instability behavior to make valid  $K_{Id}$  measurements and establish minimum time conditions. To achieve this goal, we have concentrated on developing a new impact test configuration that can be used to obtain both dynamic fracture toughness data and information about the minimum time to fracture in a relatively simple manner.

Last year, we developed an experimental technique to produce stress pulses of controlled duration in single-edge notched (SEN) specimens. The apparatus consisted of two hammers simultaneously hitting an anvil on both sides of the SEN specimen.<sup>2</sup> This year, we simplified the configuration by using a single hammer that impacts an edge-cracked bend (ECB) specimen (for example, as in the Charpy test or the drop-weight tear test).

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<sup>1</sup>Shockey, D. A., "Fracture of Structural Materials under Dynamic Loading," SRI Final Technical Report on Contract AFOSR/F49620-77-C-0059 (March 1981).

<sup>2</sup>Shockey, D. A., and Giovanola, J. H., "Dynamic Fracture Behavior of Structural Materials," SRI First Annual Report on Contract AFOSR/F49620-81-K-007 (March 1982).

The new procedure for a simple  $K_{Id}$  test is based on the improved understanding of the dynamics of impacted bend specimens as a result of recent studies.<sup>3</sup> These studies indicate that the stress intensity history for an unsupported ECB specimen impacted at the midsection has approximately a sinusoidal shape (Figure 1). The amplitude  $K_{max}$  of the curve depends mainly on the impact velocity, but also on the specimen dimensions and the mass ratio of the specimen and hammer. The duration  $\tau$  of the oscillation is essentially half the period of the fundamental mode of vibration of the specimen.

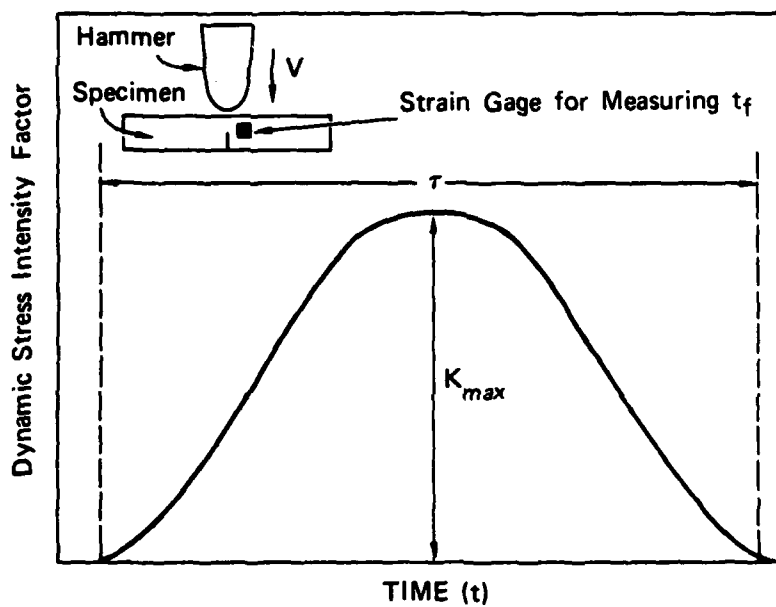
The sinusoidal stress intensity history of impacted ECB specimens is very similar to the stress intensity history obtained in SEN specimens loaded by stress pulses.<sup>4</sup> Thus, the impacted ECB specimen is as suitable as the SEN for determining valid  $K_{Id}$  values and measuring the minimum time to fracture. Moreover, the experiment is much simpler to perform and analyze. The stress intensity history is measured by placing a strain gage near the crack tip. The strain gage also allows the time  $t_f$  to be measured at which crack instability occurs.  $K_{Id}$  is obtained from the amplitude of the strain gage signal at the time  $t_f$  using either the analytical singularity solution for the stresses near the crack tip or a static calibration procedure.

Test conditions in which wave propagation effects are negligible can be achieved by using specimens with a long period (600 to 1000  $\mu s$ ) so that  $c_1 t_f / a > 40$  and by impacting at low velocities so that  $K_{max}$  only slightly exceeds  $K_{Id}$  (low K-rate experiments). This type of test can be performed on a Charpy machine. On the other hand, situations in which the wave propagation effects become dominant can be created by using high impact velocities and thus by overloading the crack. Then  $c_1 t_f / a$  values close to unity can be obtained (high K-rate experiments).

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<sup>3</sup>Kalthoff, J. F., Böhme, W., Winkler, S., and Klemm, W., "Measurements of Dynamic Stress Intensity Factors in Impacted Bend Specimens," presented at the CSNI meeting on "Instrumented Precracked Charpy Testing" at the Electric Power Research Institute, Palo Alto, CA, (December 1980).

<sup>4</sup>Homma, H., Shockey, D. A., and Murayama, Y., "Response of Cracks in Structural Materials to Short Pulse Loads," Journal of Mechanics and Physics of Solids, (1983), in press.



JA-318583-22

FIGURE 1 STRESS INTENSITY HISTORY FOR ECB SPECIMEN WITHOUT SUPPORTS

To verify that high-strength materials could be fractured in impact experiments using a Charpy tester and the unsupported ECB specimen arrangement, we first performed two low K-rate tests. The specimens were made of 4340 steel in the  $R_c50$  condition and were instrumented with a strain gage placed near the crack tip. One test was performed at room temperature and the other at liquid nitrogen temperature. In both cases, the specimens were fractured, demonstrating that the proposed approach to measure  $K_{Id}$  in a Charpy tester is feasible. Estimates of the dynamic fracture toughness  $K_{Id}$  obtained from these tests are in line with reported values.

Additional impact tests were performed on specimens with blunt notches to investigate the influence of the specimen dimensions on the duration  $\tau$  and the maximum amplitude  $K_{max}$  of the stress intensity history.

Four specimen sizes were tested. We found that for certain specimens, higher order oscillations were superimposed on the fundamental mode. This is an important finding because higher order oscillations are an undesired feature that complicates the interpretation of the dynamic fracture test. This experimental parametric study demonstrated that through proper choice of the specimen dimensions higher mode vibrations could be avoided.

The results of the blunt notch tests were compared with the predictions of a simple analysis developed in parallel with the experiments. The analysis gives  $\tau$  and  $K_{max}$  as a function of specimen dimensions, impact velocity, peak hammer load, and the mass ratio of specimen to hammer. The analysis is based on simple beam theory considering only the first mode of vibration, and we calculate the first natural frequency of the beam using Rayleigh's method and the compliance of the cracked beam. Predictions of the specimen period are in good agreement with measured values (within about 10%). The value of  $K_{max}$  is calculated from energy and momentum conservation considerations assuming a sinusoidal hammer load history of half the specimen period. The accuracy of the  $K_{max}$  predictions will be evaluated once the Charpy tester used in the experiments has been instrumented for hammer load measurements.

The analytical formula for calculating  $\tau$  and  $K_{max}$  will be useful in choosing specimen dimensions that give the desired period, amplitude, and loading rate.

### Toughness Measurements for Fast Running Cracks

The high stresses and strains in the vicinity of a crack tip cause near crack-tip material to flow plastically, and it is this plastic deformation that governs the material's toughness or resistance to fracture. Because most of the energy absorbed in plastic deformation is dissipated as heat, material near a fast-running-crack tip experiences slight increases in temperature. Thus, if these temperatures can be measured with sufficient spatial, temporal, and thermal resolution, the data can be used to solve the heat flow equations to compute the heat liberated by the crack, hence the energy absorbed in plastic deformation, and hence the propagation toughness  $K_{ID}$ .

Thus, to achieve our goal of evaluating  $K_{ID}$  for fast running cracks by means of temperature measurements, we have evaluated the laser thermoprobe technique for heat of fracture experiments and have performed six dynamic crack propagation experiments.

In the evaluation of the laser thermoprobe technique, we theoretically analyzed the absorption edge characteristics of monocrystalline CdS and annealed vapor-deposited CdS films. The theoretical predictions agreed remarkably well with laboratory measurements. On the basis of these results, we demonstrated that by using a single crystal or an annealed vapor-deposited CdS film and a stabilized argon laser, a temperature resolution of 0.03 K is achievable. However, this resolution requires a complex and delicate experimental procedure. For heat of fracture measurements, the gain in resolution over simpler techniques, such as thermocouples and thermistors, does not warrant the increased complexity of the test. Therefore, the laser thermoprobe, although operational, was not used in the heat of fracture experiments performed this year and will be reserved for applications in which spatial and time resolution as well as temperature resolution are crucial.

The main purpose of the dynamic crack propagation experiments was to obtain simultaneous measurements of the energy delivered to the running crack tip [ $K_I^{dyn}(t)$ ] and of the energy absorbed in propagating the crack [ $K_{ID}$ ].\*

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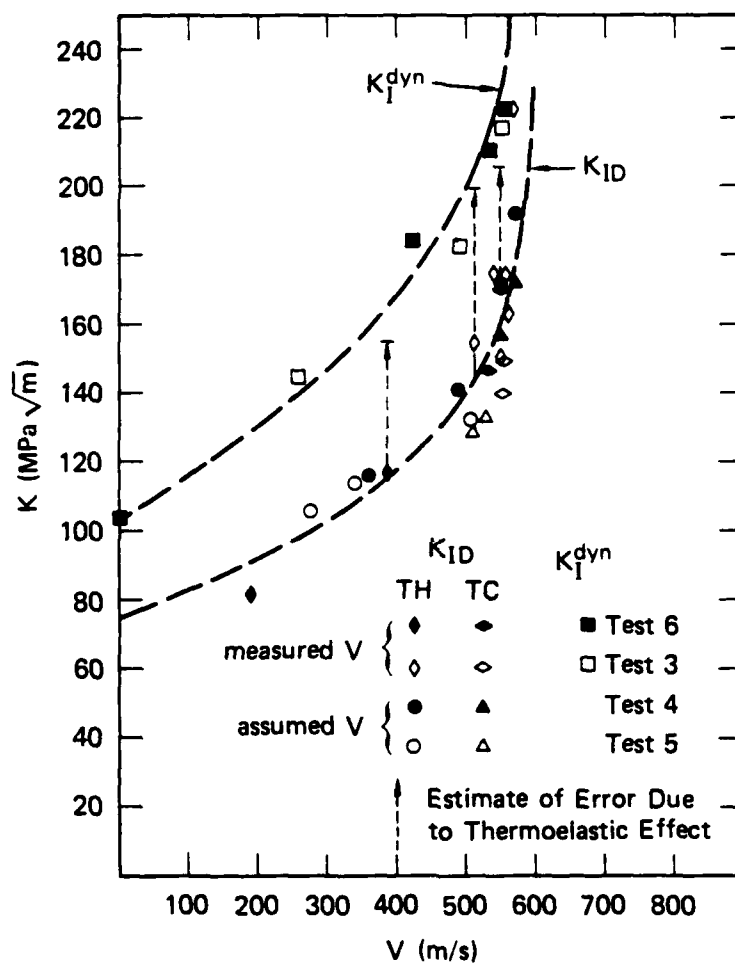
\*Energies are proportional to the squares of the K-values.

We also wanted to assess the performance of various temperature transducers (thermistors and thermocouples) and to develop an adequate testing procedure.

Six transverse wedge-loaded compact specimens of aircraft quality 4340 steel ( $R_c 50$  condition) were tested. The specimens were instrumented with four strain gages evenly spaced along the expected crack path. Two spot-welded thermocouples (TC) and four thermistors (TH) were also placed at regular intervals a few millimeters away from the crack path. The strain gages measured the crack velocity and the applied dynamic stress intensity factor  $K_I^{dyn}(t)$ . The propagation toughness  $K_{ID}$  was obtained from the thermocouple and thermistor temperature measurements.

Four out of the six tests were successful, and all four were performed under similar conditions ( $K_{IQ}$  between 214 and 253  $\text{MPa}\sqrt{\text{m}}$  and crack speed between 0 and 600 m/s). In each test the cracks were arrested. The results of the four tests are summarized in Figure 2. The curve in the upper part of the figure represents the variation of  $K_I^{dyn}$  with crack velocity; the lower curve represents the variation of the propagation toughness  $K_{ID}$  with crack velocity as deduced from the temperature measurements. Large differences are observed between  $K_I^{dyn}$  and  $K_{ID}$  at any given crack velocity. If energy rates instead of stress intensities are compared, these differences amount to up to 100%. However, these large differences may not really reflect a large imbalance between the energy delivered to and absorbed at the running crack tip. Rather, it appears that most of these large differences are attributable to perturbations in the temperature measurements because of the thermoelastic effect. On elastic loading, this effect causes a local cooling or heating of the material, depending on whether the mean stress is tensile or compressive. This happened during loading of the specimen before crack instability occurred and during reloading for a short time after crack arrest (until the machine was switched off). This thermoelastic temperature change is of the same order of magnitude as that induced by the heat of fracture and thus could represent an important source of error.

Therefore, the influence of the thermoelastic effect will have to be minimized in future experiments. This will be achieved by using a servo-controlled machine to load the specimen at a higher rate and immediately stop the displacement of the loading wedge once the crack has propagated and arrested.



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FIGURE 2 RESULTS OF DYNAMIC CRACK PROPAGATION EXPERIMENTS

The results of Figure 2 also indicate that thermistors and thermocouples performed equally well and yielded consistent data. Although thermocouples are less sensitive than thermistors, they have a faster response and are easier to handle and calibrate. Therefore, they will be used for the experiments planned in Year 4 of the program.

More details about the crack propagation experiments will be presented in a technical report currently in preparation.



## V PUBLICATIONS AND PRESENTATIONS

Papers prepared or published and presentations made during the previous program and under the current contract are listed below.

### Publications

J. F. Kalthoff and D. A. Shockey, "Instability of Cracks Under Impulse Loads," J. Appl. Phys. 48 (3), 984-993 (March 1977).

D. A. Shockey, J. F. Kalthoff, H. Homma, and D. C. Erlich, "Criterion for Crack Instability Under Short Pulse Loads," Advances in Fracture Research, D. Francois et al., Eds. (Oxford and Pergamon Press, New York), (1980), pp. 415-423.

D. A. Shockey, J. F. Kalthoff, and D. C. Erlich, "Evaluation of Dynamic Crack Instability Criteria," International Journal of Fracture Mechanics (1983), in press.

D. A. Shockey, J. F. Kalthoff, W. Klemm, and S. Winkler, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," Experimental Mechanics (1983), in press.

H. Homma, D. A. Shockey, and Y. Murayama, "Response of Cracks in Structural Materials to Short Pulse Loads," Journal of the Mechanics and Physics of Solids (1983), in press.

D. A. Shockey, J. F. Kalthoff, H. Homma, and D. C. Erlich, "Response of Cracks to Short Pulse Loads," Proceedings of the Workshop on Dynamic Fracture, W. G. Knauss, Ed., held at the California Institute of Technology, Pasadena, CA, under sponsorship of the National Science Foundation and the Army Research Office, Feb. 17-18, 1983.

### Presentations

D. C. Erlich and D. A. Shockey, "Instability Conditions for Cracks Under Short-Duration Pulse Loads," Topical Conference on Shock Waves in Condensed Matter, meeting of the American Physical Society, Washington State University, Pullman, Washington, June 11-13, 1979.

D. A. Shockey, "Instability Conditions for Cracks Loaded by Short Stress Pulses," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, December 12, 1979.

D. A. Shockey, "Dynamic Crack Instability," Institut CERAC, Ecublens, Switzerland, May 19, 1980.

D. A. Shockey, "Dynamic Crack Instability," Institut für Werkstoffmechanik, Freiburg, Germany, May 21, 1980.

D. A. Shockey, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," Poulter Laboratory Seminar, SRI International, Menlo Park, CA (June 1980).

D. A. Shockey, "Criterion for Crack Instability Under Short Pulse Loads," Fifth International Conference on Fracture (ICF5), Cannes, France, March 29-April 3, 1981.

D. A. Shockey, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," 18th Annual Meeting of the Society of Engineering Science, Inc., Brown University, Providence, RI, Sept. 2-4, 1981.

D. A. Shockey, "Response of Cracks to Short Pulse Loads," Workshop on Dynamic Fracture sponsored by NSF and ARO held at the California Institute of Technology, Pasadena, CA, Feb. 17-18, 1983, W. G. Knauss, Organizer.

D. A. Shockey, "Short Pulse Fracture Mechanics," Seminar for the Department of Applied Mechanics, Stanford University, Stanford, CA, March 3, 1983, C. Steele, Chairman.

D. A. Shockey, "Short Pulse Fracture Mechanics," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, to be presented April 11, 1983.

#### LIST OF PERSONNEL

Dr. D. A. Shockey, Principal Investigator  
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Mr. H. Yamada  
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